W Boson Production and Mass at the Tevatron

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Abstract

The CDF and DØ collaborations have analyzed up to $\sim$200 pb^{-1} of Run 2 physics data to measure *W* production properties such as the *W* cross section, the *W* width, lepton universality and the *W* charge asymmetry. From the cross section measurements, CDF obtains a lepton universality of $\frac{g_\mu}{g_e} = 0.998 \pm 0.012$ and $\frac{g_\tau}{g_e} = 0.99 \pm 0.04$ and an indirect *W* width of Γ_W=2079$\pm$41 MeV. DØ measured the *W* width directly and finds Γ_W=2011$\pm$142 MeV. CDF has estimated the uncertainties on the *W* boson mass measurements in the electron and muon decay channels and obtains an overall uncertainty of 76 MeV.

1 Introduction

The properties of the *Z* boson have been measured to very high precision at LEP [1]. Naturally one wants to match this precision for the charged carriers of the electroweak interaction. Over the next few years the Tevatron is the only accelerator which can produce *W* bosons. Measuring the properties of the *W* boson to a very high precision is an important test of the Standard Model. From the measured *W* cross section, one can infer an indirect measurement of the *W* width and lepton universality. Since at the Tevatron the *W* bosons are produced through quark anti-quark annihilation, a significant uncertainty for all direct electroweak measurements comes from the knowledge of the parton distributions inside the proton. The probability of finding a parton carrying a momentum fraction *x* within the incoming proton is expressed in the parton distribution function (PDF). The measurement of the *W* charge asymmetry provides important input on the ratio of the *u* and *d* quark components of the PDF and will help to further constrain parton distribution functions. The *W* boson mass serves as a test of the Standard Model, but through radiative corrections is also sensitive to hypothetical new particles. Together with a precise measurement of the top quark mass [2], the *W* boson mass constrains the mass of the Higgs boson, which has not yet been observed experimentally.

Both CDF and DØ are multi-purpose detectors. They consist of tracking systems surrounded by calorimeter and muon identification systems. CDF's tracking system consists of a wire drift chamber (the Central Outer Tracker) and a 7-layer silicon microstrip vertex detector (SVXII) immersed in a 1.4 T magnetic field. A lead (iron) scintillator sampling calorimeter is used for measuring electromagnetic (hadronic) showers. DØ employs a silicon microstrip tracker (SMT) and a central fiber tracker (CFT), both located in a 2 T magnetic field. The sampling calorimeter consists of liquid argon and uranium.

Since the hadronic decay of the *W* boson has an extremely large background originating from strongly interacting processes, CDF and DØ use the clean leptonic decays to study the *W* boson. The signature is a high energy lepton with large missing transverse momentum originating from the neutrino, which does not interact with the detector. The momentum balance in the direction of the beam is unconstrained and as a result, the *W* events are studied in the plane transverse to the beam. A typically used quantity is the transverse mass:

$$M_T = \sqrt{2p_T^l p_T^\nu (1 - cos(\Delta\phi))}, \tag{1}$$

which is similar to the invariant mass, just in the two transverse dimensions. If not otherwise stated, we restrict the lepton identification to the well instrumented central region of $|\eta| < 1$.

Z boson events are identified by two high energy leptons. These events have very low background.

2 Inclusive $p\bar{p} \to W/Z + X$ Cross Section Measurements

W and Z bosons are identified by their leptonic decays to electrons, muons and taus, from which the total rates $\sigma \times \mathrm{Br}(W \to l\nu)$ and $\sigma \times \mathrm{Br}(Z \to ll)$ are obtained. The cross section times branching ratio is calculated as follows:

$$\sigma \times Br(p\bar{p} \to W/Z \to ll) = \frac{N_{cand} - N_{bkg}}{A\epsilon L}. \tag{2}$$

The W and Z boson cross sections have been measured by CDF [3] with different datasets in different sub-detectors. Figure 1 shows a summary of the CDF and DØ cross section measurements in all lep-
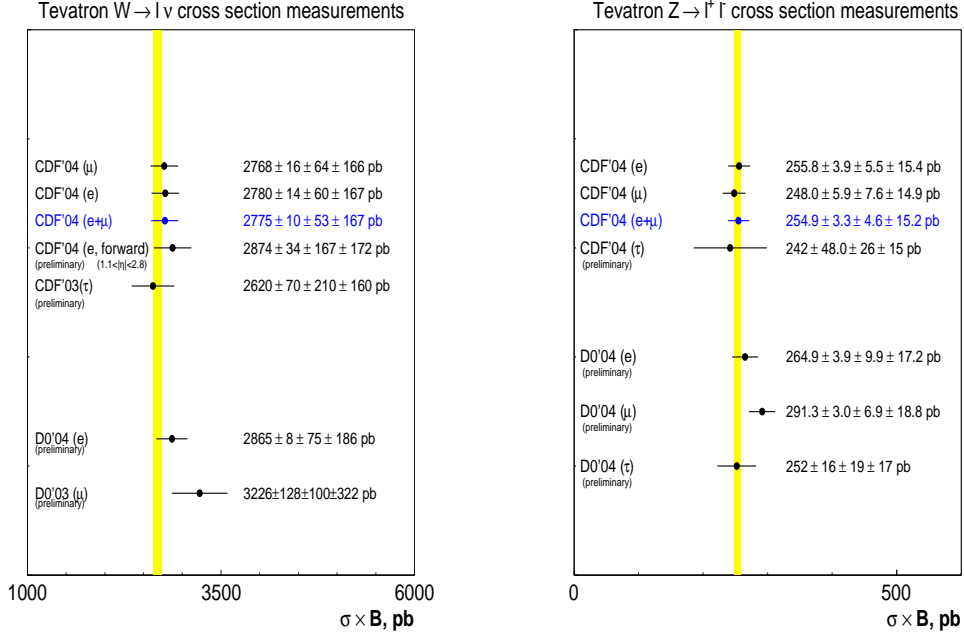

Figure 1: *Summary of various CDF and DØ W and Z cross section measurements in all three leptonic decay channels, using different datasets and sub-detectors. The uncertainties are listed in the following order: statistical, systematic, and luminosity.*

tonic decay modes. All measurements show good agreement with NNLO calculations [4], represented by the vertical band.

2.1 Lepton Universality in W Decays

Lepton universality in W decays can be tested by extracting the ratio of the electroweak couplings g_μ/g_e and g_τ/g_e from the measured ratio of $W \to l\nu$ cross sections. The $W \to l\nu$ couplings are related to the measured production cross section ratio U as follows:

$$U = \frac{\sigma \times Br(W \to l\nu)}{\sigma \times Br(W \to e\nu)} = \frac{\Gamma(W \to l\nu)}{\Gamma(W \to e\nu)} = \frac{g_l^2}{g_e^2} \tag{3}$$

In this ratio, important systematic uncertainties cancel. The results obtained are [3]:

$$\frac{g_\mu}{g_e} = 0.998 \pm 0.012 \tag{4}$$

$$\frac{g_\tau}{g_e} = 0.99 \pm 0.04 \tag{5}$$

where the largest systematic uncertainty comes from event selection efficiencies. Since these efficiencies are measured using the $Z \to ll$ sample, the uncertainty will decrease as more Z bosons are collected.

2.2 Indirect W Width Determination

The ratio R of the cross section measurements for W and Z bosons can be used to extract the total width of the W boson. R can be expressed as:

$$R = \frac{\sigma(p\bar{p} \to W)}{\sigma(p\bar{p} \to Z)} \frac{\Gamma(W \to l\nu)}{\Gamma(Z \to ll)} \frac{\Gamma(Z)}{\Gamma(W)}. \tag{6}$$

Using the very precise measurement of $\Gamma(Z \to ll)/\Gamma(Z)$ from LEP and NNLO calculations of $\sigma(p\bar{p} \to W)/\sigma(p\bar{p} \to Z)$, together with the Standard Model prediction of $\Gamma(W \to l\nu)$ one can extract $\Gamma(W)$ from equation 6. Table 1 shows the values from CDF for two different datasets, together with the

Table 1: *Summary of indirect W width measurements.*

Channel	$\Gamma(W)(MeV)$	L (pb^{-1})
$W \to e\nu + W \to \mu\nu$	2079 ± 41	72
$W \to \mu\nu$	2056 ± 44	194
World average	2124 ± 41	

current world average (not including these measurements). The indirect width measurements show good agreement and have competitive uncertainties.

3 Direct W Width Measurement

DØ has measured the W boson width directly in the electron decay channel [5]. The measurement uses an integrated luminosity of 177 pb^{-1}. The width is determined by normalizing the predicted signal and background transverse mass distribution in the region of 50 GeV$<M_T<$100 GeV and then fitting the predicted shape to the candidate events in the tail region 100 GeV$<M_T<$200 GeV, which
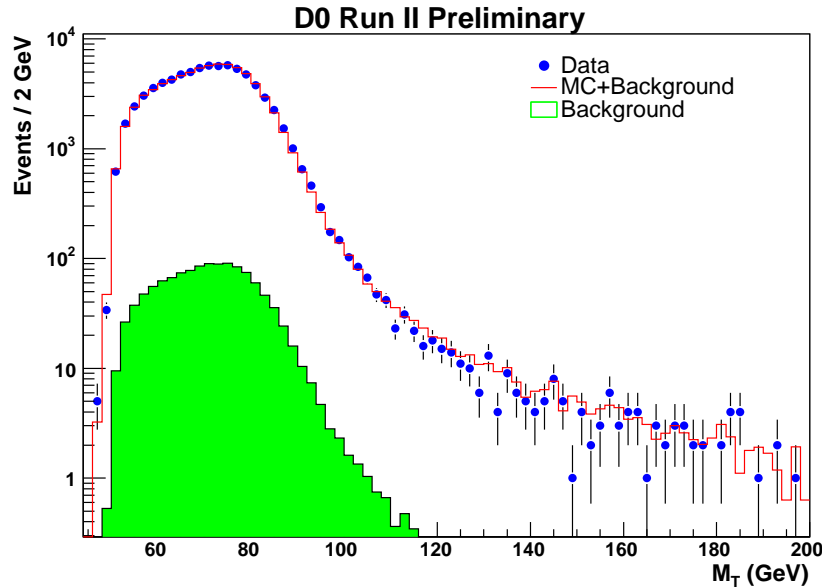

Figure 2: *W width extraction from high transverse mass tail.*

is most sensitive to the width. Figure 2 shows the transverse mass distribution. The measurement yields $\Gamma_W = 2011\pm93(\mathrm{stat})\pm107(\mathrm{syst})$ MeV, which is in good agreement with the world average, an improvement over the DØ Run 1 measurement [6], and competitive to the CDF Run 1 measurements in the muon and electron decay channels [7].

4 W Charge Asymmetry

The W bosons at the Tevatron are produced predominantly through annihilation of valence u (d) and anti-d (anti-u) quarks inside the proton and anti-protons for W^+ (W^-) production. Since u quarks carry, on average, a higher fraction of the proton momentum than d quarks, a W^+ tends to be boosted in the proton direction, while a W^- is boosted in the anti-proton direction. This results in a non-zero forward-backward charge asymmetry, defined as:

$$A(y_W) = \frac{d\sigma(W^+)/dy_W - d\sigma(W^-)/dy_W}{d\sigma(W^+)/dy_W + d\sigma(W^-)/dy_W},\tag{7}$$

where y_W is the rapidity of the W bosons and $d\sigma(W^\pm)/dy_W$ is the differential cross section for W^+ or W^- boson production. However, because the p_Z of the neutrino is unmeasured, y_W cannot be directly determined, and we instead measure:

$$A(\eta_e) = \frac{d\sigma(e^+)/d\eta_e - d\sigma(e^-)/d\eta_e}{d\sigma(e^+)/d\eta_e + d\sigma(e^-)/d\eta_e},\tag{8}$$

where η_e is the electron pseudorapidity. Therefore, the observed asymmetry is a convolution of the aforementioned charge asymmetry and the Standard Model $V - A$ couplings describing the $W \to e\nu$ decays. A measurement of the forward-backward charge asymmetry is sensitive to the ratio of the u and d quark components of parton distribution functions. CDF has measured this asymmetry in the electron channel up to a pseudorapidity of $|\eta|<2.5$ using 170 pb^{-1} [8]. Figure 3 shows the measured
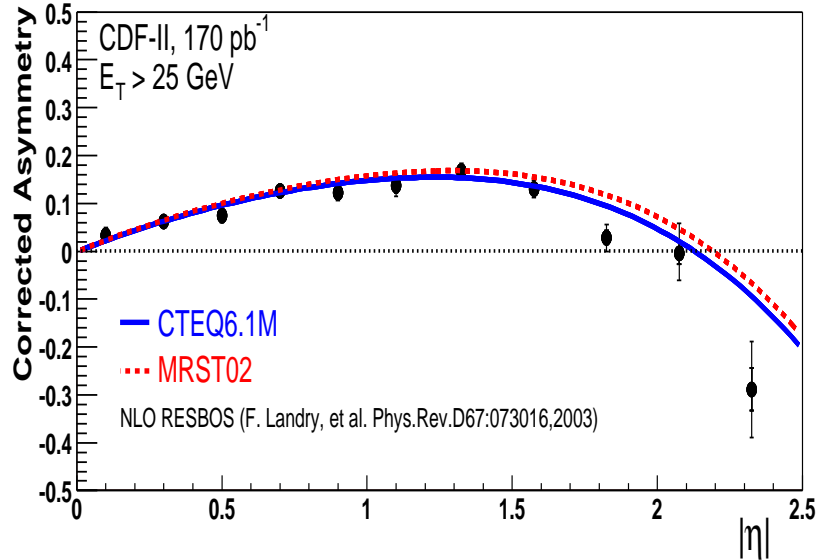

Figure 3: *Measured asymmetry corrected for the effects of charge misidentification and background contributions.*

asymmetry corrected for the effects of charge misidentification and background contributions. The predictions using the latest CTEQ and MRST PDFs are overlaid. This measurement will provide important input for the next generation of PDFs.

5   *W* Mass

Since its discovery in 1983 [9] [10], the *W* boson mass has been measured with increasing precision. From an initial uncertainty of 5 GeV, the uncertainty of the *W* mass has been reduced to 42 MeV from the LEP experiments [11] and to 59 MeV from the Tevatron experiments [7]. CDF has analyzed the first 200 pb^{-1} of Run 2 data and estimated the corresponding *W* boson mass uncertainty in the electron and muon decay channels. The uncertainty includes contributions from statistics, production and decay modeling, lepton energy scale and resolution, hadronic recoil and resolution, and backgrounds.

There are two important aspects to a precision *W* mass measurement: Calibration of the detector to the highest possible precision, and simulation of the transverse mass spectrum, which cannot be predicted analytically. The simulation includes the production modeling and detector effects and produces transverse mass templates for a range of *W* boson masses. Since backgrounds contaminate the signal, they are included in the templates. The *W* mass is extracted from a maximum likelihood fit to the transverse mass spectrum.

5.1   Production Model

The uncertainty in the modeling of the *W* boson production and decay results from parton distribution functions, QED radiative corrections, the transverse momentum of the *W* boson and the *W* boson width.

The parton distribution functions affect the *W* mass through the limited acceptance of the detector for the *W* decay lepton. The uncertainty has been determined using the set of 40 CTEQ6 PDFs [12], which explore the uncertainty on the 20 orthogonal eigenvector directions in parameter space. Each eigenvector direction corresponds to some linear combination of PDF parameters. The resulting uncertainty is $\Delta M_W(e, \mu) = \pm 15$ MeV. A cross check using the latest MRST [13] PDF falls within this estimate.

The dominant higher-order QED effect on the *W* boson mass is photon radiation off the final-state charged lepton. Additional QED uncertainties arise from multi-photon radiation, initial state radiation and radiation from interference terms, none of which are included in the simulation used to extract the *W* boson mass. The uncertainty from QED corrections is $\Delta M_W(\mu) = \pm\ 20$ MeV in the muon channel and $\Delta M_W(e) = \pm 15$ MeV in the electron channel.

The initial-state QCD radiation in vector boson production is constrained by a phenomenological parametrization of the *Z* boson p_T measurement from the previous collider run. The parameters are used for the modeling of the *W* p_T distribution and their uncertainties result in $\Delta M_W(e, \mu) = \pm 13$ MeV.

The uncertainty on the *W* boson width affects the falling Jacobian edge and leads to $\Delta M_W(e, \mu) = \pm 12$ MeV.

5.2   Lepton Momentum/Energy Scale and Resolution

The lepton momentum measurement is based fundamentally on the calibration of the tracking wire chamber (COT). After the calibration of the track momentum and resolution using the muon decays of precisely known resonances, the energy scale of the electromagnetic calorimeter is calibrated using the ratio of calorimeter energy to track momentum (E/p) of electrons.

The quarkonium resonance decays $J/\Psi \rightarrow \mu\mu$ and $\Upsilon(1S) \rightarrow \mu\mu$ are used to set the momentum scale (Figure 4). The passive material in the simulation is tuned such that the reconstructed J/Ψ mass is constant as a function of mean track curvature. The measured momentum scale is the mean of the individual J/Ψ and $\Upsilon(1S)$ scales. The systematic uncertainty is taken as half the difference between the extracted scales which results in $\Delta M_W(e, \mu) = \pm 15$ MeV.

The track resolution is parametrized in the simulation by the individual hit resolution and by the hit multiplicity on the track. Muons from decays of *Z* bosons are used to determine the resolution. The resulting uncertainty corresponds to $\Delta M_W(e, \mu) = \pm 12$ MeV. An additional uncertainty of $\Delta M_W(e, \mu) = \pm 20$ MeV is assigned for tracking chamber misalignments.
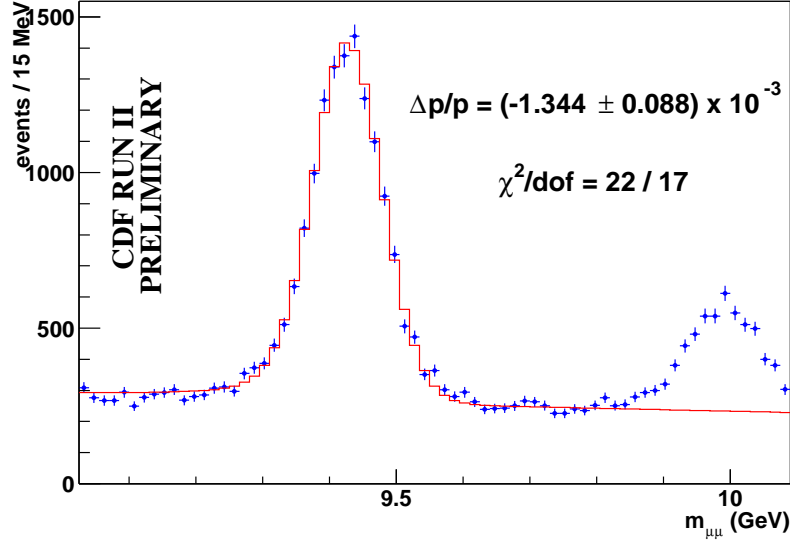
Figure 4: *The reconstructed invariant mass of muon candidate pairs in the $\Upsilon(1S)$ region. The fractional difference between the measured and PDG mass is shown.*

The E/p distribution of electrons from W boson decays is used to calibrate the electromagnetic energy scale of the calorimeter (Figure 5). The statistical uncertainty and the uncertainty from the momentum scale results in $\Delta M_W(e) = \pm 35$ MeV. Additional energy scale uncertainties arise from the calibration of the detector passive material and from the calorimeter non-linearity. The passive material was measured during detector construction and is tuned using electrons from photon conversions. A final tuning uses the tail of the E/p distribution which is sensitive to the amount of material modeled in the simulation. The uncertainty on the passive material results in $\Delta M_W(e) = \pm 55$ MeV. The calorimeter non-linearity is determined from the E_T dependence of the energy scale. After applying a correction, the uncertainty on the slope results in $\Delta M_W(e) = \pm 25$ MeV.

The calorimeter resolution is parametrized as $\sigma E_T/E_T = 13.5\%/\sqrt{E_T} \oplus \kappa$, where κ is determined from the width of the E/p signal. The uncertainty on κ results in $\Delta M_W(e) = \pm 7$ MeV.

The Z boson masses are used as cross checks for the momentum and energy scales.

5.3 Recoil Scale and Resolution

The hadronic recoil is measured by summing over the energy in all calorimeter towers, excluding the lepton towers. The simulation removes an equivalent set of towers by subtracting the mean underlying event energy as measured from adjacent towers. The uncertainty on the measurement of this underlying event energy results in $\Delta M_W(e) = \pm 15$ MeV and $\Delta M_W(\mu) = \pm 10$ MeV uncertainties on the W mass.

The hadronic recoil scale is the ratio of measured to true recoil. It is parametrized as a function of the true recoil and tuned using Z events where both decay leptons are reconstructed and the Z boson p_T can be reconstructed precisely from the lepton momentum measurements. The uncertainty on the parametrization results in $\Delta M_W(e, \mu) = \pm 20$ MeV.

The recoil resolution model incorporates terms from the underlying event, which are modeled with generic inelastic collisions, and from hadronic jet resolution. The resolution uncertainty results in $\Delta M_W(e, \mu) = \pm 42$ MeV.
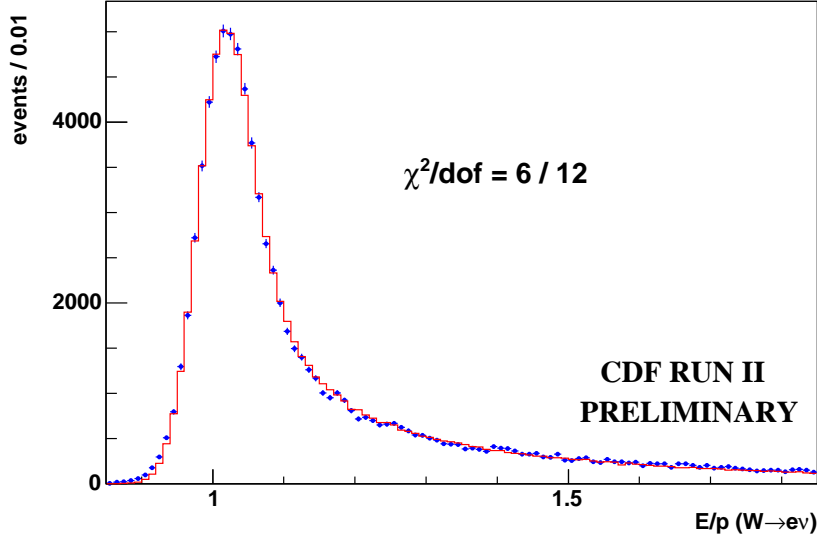
Figure 5: *The E/p distribution of electrons from W boson decays. The region between 0.95 and 1.1 is used for the calibration of the electromagnetic energy scale.*

5.4 Backgrounds

The backgrounds in the W boson data sample include $W \to \tau\nu$, $Z \to ll$ where one lepton is outside the detector acceptance and not reconstructed, hadronic jets, where one jet mimics a lepton, cosmic rays, where one leg of the cosmic track is not reconstructed, and kaon decays, where the kaon track is misreconstructed, resulting in large apparent muon momentum. The background measurement uncertainties result in $\Delta M_W(e, \mu) = \pm 20$ MeV.

5.5 Mass Fits and Total Uncertainty

After including all measurement components, CDF obtains transverse mass (Figure 6) and transverse energy distributions which are well modeled. Table 2 summarizes the uncertainties for the M_T fits in the electron and muon decay channels. For comparison the uncertainties from the previous collider

Table 2: *The uncertainty on the W boson mass measurement using $\sim$200 pb^{-1} of Run 2 CDF data. The CDF Run 1b uncertainties are shown for comparison.*

Uncertainty	Electrons (Run 1b)	Muons (Run 1b)
Production and Decay Model	30 (30)	30 (30)
Lepton Energy Scale and Resolution	70 (80)	30 (87)
Recoil Scale and Resolution	50 (37)	50 (35)
Backgrounds	20 (5)	20 (25)
Statistics	45 (65)	50 (100)
Total	105 (110)	85 (140)

run [14] (Run 1b) are also included. The overall uncertainty is 76 MeV. The W boson mass fit results are currently blinded with a constant offset. The offset will be removed when further cross checks have been completed.
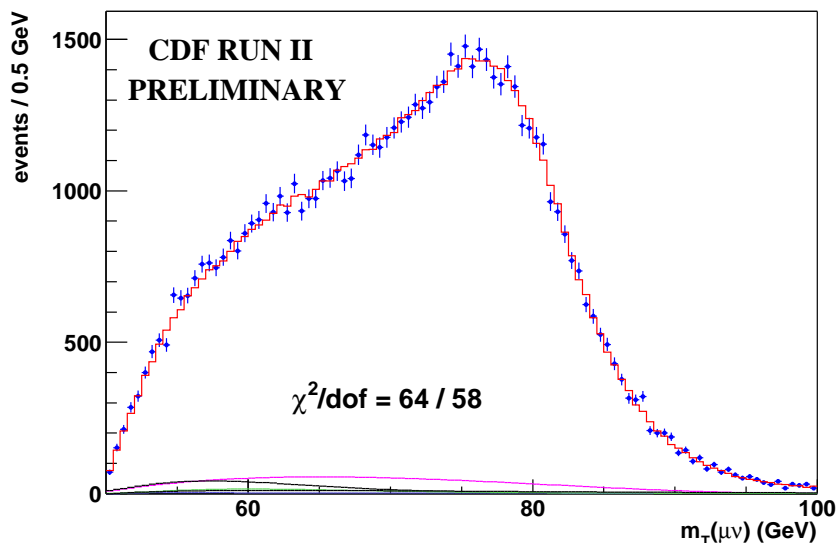
Figure 6: *The M_T distribution in W boson decays to muons. The points represent the data, the histogram the simulation with backgrounds added. The region between 60-90 GeV is used to fit the W boson mass.*

6 Summary

The W boson physics program at the Tevatron is very successful. CDF and DØ have measured the inclusive W and Z cross sections in all three leptonic decay channels, which show good agreement with NNLO calculations. From the cross section measurements, CDF has extracted competitive measurements on lepton universality and an indirect measurement of the W boson width. DØ has measured the W boson width directly in the electron channel with an uncertainty smaller than the Run 1 value. The new CDF W charge asymmetry will help to further constrain the uncertainties of parton distribution functions, which affect all the aforementioned measurements. With the addition of 600 pb^{-1} of data on tape, these measurements will further constrain the Standard Model.

CDF has determined the uncertainty on the W boson mass with the first ∼200 pb^{-1} of Run 2 data to be 76 MeV, which is lower than its Run 1 uncertainty of 79 MeV. With the additional data to come, Run 2 promises the world's highest precision measurement of the W boson mass, with an anticipated uncertainty of 30 MeV for 2 fb^{-1}.

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